# Mineral mapping for porphyry copper exploration using multispectral satellite and hyperspectral airborne sensors

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# ABSTRACT

Alteration minerals associated with porphyry copper deposits have absorption features in the visible through shortwave infrared (VIS-SWIR, 0.4-2.5 $\mu$ m) and/or the long-wave infrared (7.5-13.5  $\mu$ m). Regional mineral exploration can be conducted using the NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (AS-TER) sensor to develop prospects. Potential targets can then be further refined using hyperspectral sensors such as the commercial Hyperspectral Mapper (HyMap) and the Spatially Enhanced Broadband Array Spectrograph System (SEBASS). Mineral mapping, with these hyperspectral sensors focused on the minerals associated with the deposit model, allows for rapid characterization of the surface geology that would require many man-years if done by traditional mapping.

ASTER is a multispectral satellite sensor that measures the reflectance and emission of materials in the visible and short-wave infrared (VIS-SWIR) parts of the electromagnetic spectrum. SEBASS is a hyperspectral sensor that can measure mineral absorption features in the mid-wave infrared (2.5-5.3  $\mu$ m) and the long-wave infrared (7.5-13.5  $\mu$ m). HyMap is a hyperspectral sensor that can measure mineral absorption features in the VIS-SWIR (0.45-2.5  $\mu$ m) part of the spectrum. In 1999 SEBASS and HyMap data were collected over Yerington, Nevada, and an ASTER scene was collected in 2001.

Logical operators were used to process the ASTER data for alteration minerals associated with porphyry copper deposits. Mineral maps were produced using a spectral feature algorithm with publicly available libraries containing the spectral signatures of minerals considered in our porphyry copper deposit model. These mineral maps can be integrated into an exploration database and combined with other geophysical data to refine prospect development. This study shows that regional and prospect exploration can benefit from using satellite and airborne multispectral and hyperspectral sensors processed in accordance with a deposit model.

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# INTRODUCTION

Regional porphyry copper exploration projects commonly use spaceborne multispectral sensors such as Landsat and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The second-generation Landsat satellites are capable of identifying spectral anomalies that may be associated with mineral alteration. ASTER with nine visible and near-infrared (VNIR) through short-wave infrared (SWIR) and five long-wave infrared (LWIR) bands are a dramatic improvement over Landsat for regional exploration. The improvement provided by ASTER data comes from an increase in the number of bands and, more importantly, from use of SWIR bands that were specifically chosen to emphasize minerals with absorption features in the SWIR spectral range.

Commercially available VNIR-SWIR hyperspectral sensors, such as HyMap and ProSpecTIR, can identify specific mineralogy through inversion image-processing methods. Hyperspectral sensors are defined by the large number (in the range of hundreds) of spectral bands. Mid-wave infrared (MWIR) and long-wave infrared (LWIR) hyperspectral sensors such as SEBASS can identify specific minerals using inversion methods similar to those used in the VNIR-SWIR spectrum. These high signal-to-noise ratio (SNR) sensors are capable of mapping changes in mineral chemistry along with identifying the same and different minerals.

Porphyry copper deposits commonly produce zoned assemblages of alteration minerals as described by Lowell and Guilbert (1970) and shown in Figure 1 of this report. The utilization of ground and airborne spectroscopy for a variety of geological applications, including mineral exploration and mine development, is possible because spectral absorption features are present in rock-forming and alteration minerals. These absorption features occur in the visible and near infrared (VNIR, 0.4-1.1 µm), short-wave infrared (SWIR, 1.1-2.5 μm), and the long-wave infrared (LWIR, 8.0-14.0 μm) portions of the electromagnetic spectrum (Abrams and others, 1983; Spatz and Wilson, 1995). Airborne hyperspectral sensors can remotely map these minerals using their associated spectral absorption features, producing mineral maps that can be evaluated alone or integrated into a geographic information system (GIS).

Identifying specific minerals in areas of interest is important for exploration, environmental impact statements, environmental health concerns, ore grading and metallurgical processing, and geotechnical mine-site planning. In exploration, hyperspectral sensors can assist in lithological and alteration mapping by covering many areas where the field geologist cannot cover and by helping to map mineralogical characteristics used in exploration. A hyperspectral data set, used to document the natural conditions of the ground prior to mine operations, will be useful for mine reclamation. Other uses of these data may include an initial mineral assessment focused on naturally occurring minerals that may have human



Figure 1. Alteration minerals and zone of porphyry copper deposits modified from Figure 3 of Lowell and Guilbert (1970).

health effects. Commercially available, non-imaging field spectrometers, such as the Portable Infrared Mineral Analyser (PIMA) or the Terraspec, have been used in exploration to assist alteration mapping, and this same technology can potentially assist the mine-site geologist in rapid ore-grade assessments.

# **GEOLOGY OF THE AREA**

The altered rocks of the porphyry and skarn deposits in Yerington, Nevada are well exposed and have been mapped in extensive detail. Moreover, the rocks have been tilted almost 90°, exposing propylitic, argillic, phyllic, and potassic alteration zones that are related to the porphyry copper deposit, and the hydrothermal fluid paths to the associated skarn deposits have been mapped (Dilles and Proffett, 2000, and Einaudi, 2000). Early multispectral and hyperspectral sensing studies (Windeler and Lyon, 1991; Cudahy and others, 2000; Cudahy and others, 2001, Cudahy and others, 2001) combined with the detailed mapping of the hydrothermal alteration and lithology (Dilles and Einaudi, 1992; Proffett and Dilles, 1984, Einaudi, 2000; Fig. 2) demonstrate the utility of mineral mapping with multispectral satellite and airborne hyperspectral instruments.

#### MINERAL SIGNATURES

#### **Propylitic alteration**

Minerals associated with propylitic alteration in porphyry copper deposits are commonly chlorite, epidote, and calcite at shallow depths of emplacement; sericite (muscovite, paragonite, illite), albite, actinolite, and magnetite commonly are found at deeper levels of emplacement (Fig. 1). These minerals have different absorption features in the SWIR and the LWIR, and the primary absorption features for chlorite,





Figure 3. VIS–SWIR (0.4-2.5  $\mu$ m) and LWIR (7.5-13.5  $\mu$ m) spectral signatures of minerals. The mineral signatures are from the USGS spectral signature library. The minerals chosen coincide with the minerals from the modified alteration zone diagram (Figure 1).

epidote, and carbonate overlap in the SWIR (Fig. 3).

Chlorite has three absorption features in the SWIR, with the deepest feature at 2.3250  $\mu$ m and two shallower features at 2.2450 and 2.3860  $\mu$ m (Fig. 3A). Epidote has two absorption features in the SWIR at 2.3350 and 2.2550  $\mu$ m. Calcite has an absorption feature in the SWIR at 2.3350  $\mu$ m. Albite does not have any significant absorption features in the SWIR part of the spectrum. Actinolite has four SWIR absorption features, which are, in declining magnitude: 2.3050, 2.3860, 1.0335, and 1.3935  $\mu$ m (Fig. 3A). albite all have different absorption features in the LWIR (Fig. 3B). Chlorite has a deep absorption feature at 9.75  $\mu$ m and two shallower absorption features at 9.35 and 10.4  $\mu$ m. Absorption features for epidote are at 8.9, 9.4, 10.4, and 11.25  $\mu$ m. Calcite has a single absorption feature at 11.3  $\mu$ m. Principal absorption features of albite are 8.7, 9.2, 9.6, and 9.9  $\mu$ m (Fig. 3B).

#### Argillic alteration

Propylitic minerals such as chlorite, epidote, calcite, and

Quartz, kaolinite, alunite, and chlorite are minerals associated with argillic alteration (Fig. 1). Other minerals such

as montmorillonite, diaspore, porphyllite, and dickite are commonly associated with argillic alteration. This paper will focus on the alteration-zone indicator minerals in Fig. 1 as example mineralogy and is not meant to be all inclusive.

Quartz does not have any absorption features in the VNIR-SWIR (Fig. 3A). Kaolinite has a four absorption features (Fig. 3A) forming two doublets at 1.4 (1.3935 and 1.4135) and 2.2 (2.1650 and 2.2050)  $\mu$ m. Alunite has three absorption features, one doublet at 1.4 (1.4285 and 1.4785)  $\mu$ m and a single absorption feature at 2.165  $\mu$ m. The absorption features of chlorite (Fig. 3A) were discussed previously in the propylitic alteration section.

The LWIR spectral signature of quartz has a doublet absorption feature with a peak centered at 8.65  $\mu$ m. Alunite has an absorption feature at 8.9  $\mu$ m. Chlorite, montmorillonite, and kaolinite are argillic hydrothermal alteration minerals and have different LWIR signatures (Fig. 3B); the spectral signature of montmorillonite is not shown in Figure 3. Na-montmorillonite has the primary absorption feature at 9.4  $\mu$ m with a secondary feature at 8.8  $\mu$ m. A broad absorption feature at 9.5  $\mu$ m is representative of Ca-montmorillonite. Kaolinite has four absorption features (8.9  $\mu$ m, 9.6  $\mu$ m, 9.9  $\mu$ m, and 11.0  $\mu$ m) with the 9.6  $\mu$ m and 11.0  $\mu$ m features being the most significant. The absorption features of chlorite do not overlap those of kaolinite or alunite in the SWIR. The absorption features of chlorite are described above.

# **Phyllic alteration**

Phyllic alteration commonly contains quartz, muscovite (sericite), and pyrite (Fig. 1); the VIS-SWIR and LWIR signatures of those minerals are shown in Figure 3. The spectral signature of quartz in the VIS-SWIR spectral range is flat, lacking absorption features. The muscovite spectrum has four absorption features in VIS-SWIR and can be distinguished from that of kaolinite because it does not form a doublet at 2.2  $\mu$ m. The four SWIR absorption features of muscovite are at 2.2050, 2.3450, 2.440, and 1.4135  $\mu$ m. Illite has three absorption features, 2.2150, 2.3460, and 1.4085  $\mu$ m (Fig. 3A).

Muscovite and quartz both have spectral absorption features in the LWIR. Quartz has a unique doublet centered at 8.6  $\mu$ m with the minima at 8.5 and 8.9  $\mu$ m and a second doublet at 12.6  $\mu$ m with minima at 12.5 and 12.8  $\mu$ m. Muscovite has two absorption features at 9.25 and 9.4  $\mu$ m (Fig. 3B).

#### **Potassic alteration**

Minerals typically associated with potassic alteration are potassium feldspar, biotite, quartz, muscovite, and anhydrite (Fig. 1). These minerals all have LWIR absorption features, and differentiating the types of potassium feldspar is important for understanding the temperature of formation and for distinguishing between potassium feldspar alteration and the host-rock mineralogy. Biotite and muscovite have absorption features in the SWIR, and quartz and muscovite signatures were discussed above in the phyllic alteration section.

Adularia, microcline, and orthoclase do not have any absorption features in the VIS-SWIR (Fig. 3). Any potassium feldspar signature with a 2.2  $\mu$ m feature indicates alteration of potassium feldspar to muscovite (Clark and others, 2007). Biotite has three absorption features: one broad absorption feature related to Fe at 1.20  $\mu$ m and two other absorption features at 2.3350 and 2.4050  $\mu$ m. Anhydrite does not have an absorption feature in the VIS-SWIR (Fig. 3A).

Anhydrite has a broad absorption feature between 8.3-8.5  $\mu$ m region of the LWIR spectrum. Orthoclase has two absorption features at 8.5  $\mu$ m and 9.5  $\mu$ m (Fig. 3B). Microcline has numerous absorption features, but the key absorption features are at 9.5 and 8.6  $\mu$ m. Adularia has two absorption features, 8.7 and 9.5  $\mu$ m. These minerals show a shift in the minima of absorption features of adularia (8.7  $\mu$ m), microcline (8.6  $\mu$ m) and orthoclase (8.5  $\mu$ m). These spectral-absorption features at wavelengths shorter than 9.0  $\mu$ m may indicate the temperature of formation, because each of these potassium feldspars has a consistent absorption feature at 9.5  $\mu$ m. Biotite has an absorption feature with the minimum centered at 9.8  $\mu$ m (Fig. 3B).

# MULTISPECTRAL AND HYPERSPECTRAL SENSORS

ASTER. The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) measures reflected radiation in three bands in the 0.52–0.86  $\mu$ m wavelength region (VNIR), six bands in the 1.6–2.43  $\mu$ m wavelength region (SWIR), and five bands of emitted radiation in the 8.125– 11.65  $\mu$ m wavelength region (TIR) (Fujisada, 1995). The AS-TER system consists of three separate sensors in the VNIR, SWIR, and TIR spectral regions and have ground-sample-distance (GSD) resolutions of 15 m, 30 m, and 90 m, respectively (Fujisada, 1995). ASTER also has a backward-looking VNIR telescope with 15 m resolution for stereoscopic VNIR image acquisition.

**HyMap**. HyMap is an airborne hyperspectral imaging spectrometer with 128 channels across three wavelength regions in the VNIR-SWIR spectrum (0.45–2.5  $\mu$ m). From 0.45–1.4  $\mu$ m there are 64 channels, 1.4-1.9  $\mu$ m there are 32 channels, and from 1.9-2.5  $\mu$ m channels there are 32 channels with bandwidths of 15-17 nm. This sensor has a 2.0 milliradian instantaneous field of view (2 mrad IFOV) and is capable of a 61.3° swath width producing imagery with 3-10 m GSD. The sensor has on-board radiometric and spectral calibration with SNR greater than 500:1 (Cocks and others, 1998).

**SEBASS**. The Spatially Enhanced Broadband Array Spectrograph System (SEBASS) measures reflected and emitted radiation in the 2.5-5.3 µm wavelength region with 128 bands and emitted radiation in the 7.5-13.5 µm wavelength region, also with 128 bands. The instrument has a 1.1-mrad IFOV per pixel and a 7.8° swath width. This sensor is commonly flown at 2,000 m above ground level (AGL) producing a 2-m resolution, but can be flown at lower or higher altitudes. The signal-to-noise resolution has been tested at more than 2,000:1 with greater area coverage (Hackwell and others, 1996).

# **METHODS**

# **Calibration of ASTER data**

A cloud-free Level 1B radiance at the sensor dataset (byte data) acquired on May 22, 2005 was downloaded from the Eros Data Center. A Level 2 Moderate Resolution Imaging Spectroradiometer (MODIS) Total Precipitable Water (MOD 05) water vapor image acquired at the same time of ASTER acquisition was downloaded from L1 and Atmospheres Archive and Distribution System (LAADS). A crosstalk-correction algorithm (Iwasaki and Tonooka, 2005) was applied to the ASTER radiance-byte data to remove crosstalk from the ASTER SWIR data. The ASTER SWIR data were resampled to 15-m resolution and combined with the ASTER VNIR data to produce a 9-band, 15-m-resolution, radiance-byte dataset. Radiance coefficients, which convert the byte to integer data, were applied to the ASTER radiance-byte data. Radiance correction factors (Biggar and others, 2005) were then applied to the ASTER radiance-integer data. The ASTER radiance-integer data were converted to reflectance using ACORN atmospheric correction software (ACORN, 2005). A MODIS water vapor average value for the ASTER coverage was obtained from the MOD 05 water vapor data and used in the atmospheric correction program to remove water vapor.

# Calibration of HyMap data

HyMap data for the Yerington district were acquired in September 2000 under clear-sky conditions. These three flight lines are approximately 2.5 km wide with a 5-m GSD. A darkcurrent subtraction had been applied to the data followed by generation of suitable calibration factors to convert the digital numbers to radiance at the sensor. After this calibration to radiance at the sensor, the data were atmospherically corrected to at surface reflectance using ACORN (2005) radiative-transfer-correction software.

# **Calibration of SEBASS data**

Under clear sky conditions, SEBASS data were collected for the Yerington district in September 1999. These data were calibrated to at-sensor radiance following the steps outlined in Hackwell and others (1996). Atmospheric compensation of these data was accomplished using an In Scene Atmospheric Correction (ISAC) algorithm (Young and others, 2002) and converted to apparent emissivity using a temperature emissivity normalization algorithm in ENVI image-processing software. The LWIR data were reduced from 128 bands to 85 bands corresponding to the 8.0–12.0  $\mu$ m region prior to analysis.

# Spectral mapping methods

A set of logical operators written in IDL were used to map argillic- and phyllic-altered rocks. Logical operators use a series of band ratios and thresholds to map a specific spectral shape. Each logical operator determines a true or false value for each ratio by comparing the band ratio to a predetermined range of threshold values. All of the ratios in the algorithm have to be true in order for a value of 1 to be assigned as a byte image, otherwise a 0 value is produced. Thus, a byte image with pixel values of 0 or 1 is produced for each algorithm. Multiple ratios and band thresholds can be applied to a scene using one algorithm, thus, eliminating the separate production and application of vegetation and dark-pixel masks. Logical operators have been used successfully to map regional alteration (Mars and Rowan, 2006).

#### Argillic band ratio logical operator algorithm

The first part of the argillic band ratio logical operator (ABRLO) algorithm performs a band 3/2 ratio to mask out green vegetation (equation A). A spectral analysis of image and library spectra suggests that band 3/2 ratio threshold values of 1.55 and less typically constitute areas that lack green vegetation. The ratio does not mask out dead vegetation, which has 2.17 and 2.33 µm absorption features.

The ABRLO algorithm performs a threshold of band 4 to mask out pixels with low reflectance that contain noise (equation A). Spectral analysis of ASTER image spectra and resampled ASTER laboratory spectra showed that band ratios 4/6, 5/6, and 6/7 were needed to map the 2.17 and 2.2  $\mu$ m absorption features, thereby delineating argillic-altered rocks. Band ratios 5/6 and 4/6 map the 2.165 and 2.2  $\mu$ m absorption features, respectively (equation A). Spectral analysis of AS-TER data indicates that the reflectance value of band 5 must be at least 8.9 percent lower than that of band 6 in order to be classified as an argillic-altered rock; thus, the 5/6 band ratio differentiates argillic-altered from phyllic-altered rocks by classifying ratio values of 1.089 and less as argillic alteration (equation A). ASTER spectra of argillic-altered rocks also illustrate that band 4 is at least 37 percent greater than band 6, and band 7 is 3 percent greater than band 6. Thus, values in the ABRLO algorithm for band ratios 4/6 and 7/6 must be greater than 1.37, and greater than or equal to 0.02, respectively, to classify a pixel as argillic alteration (equation A).

Equation A: ((((float(b3)/b2)le1.55)and(b4gt3250)and ((float(b4)/b6)gt1.37)and((float(b5)/b6)le1.089)and((float(b7)/b6)ge1.02)))

# Phyllic band ratio logical operator algorithm

The phyllic band ratio logical operator (PBRLO) algorithm is almost identical to the ABRLO algorithm. The PBRLO algorithm uses the same methods to mask green vegetation and pixels with low reflectance. ASTER spectra of phyllic-altered rocks show that band 5 is at least 8.9 percent greater than band 6, which is expressed in the PBRLO algorithm as classifying all 5/6 band ratio values greater than 1.089 as phyllic-altered rocks (equation B).

ASTER spectra also indicate that band 6 is at least 37 percent lower than band 4, and band 7 is at least 2 percent greater than band 6 (equation b). Thus, values in the PBRLO algorithm for band ratios 4/6 and 7/6 must be greater than 1.37, and greater than or equal to 0.02, respectively, in order to classify a pixel as phyllic alteration (equation b).

Equation B: ((((float(b3)/b2)le1.55)and(b4gt3250)and((float(b4)/b6)gt1.37)and((float(b5)/b6)gt1.089)and((float(b7)/b6)ge1.02)))

# Band ratio thermal infrared (TIR) data

ASTER On-Demand L2 Surface Emissivity (AST\_05) data of the same ASTER dataset were downloaded from the Eros Data Center. The 90 m data were resampled to 15-m pixel dimensions. Quartz has a strong restrahlen absorption feature at 8.65  $\mu$ m. A band ratio of ASTER band 13 divided by band 12 was used to define the restrahlen feature. Potassium feldspars have absorption features at 9.5  $\mu$ m and a 13/12 band ratio should help map these minerals.

# Alteration mapping using the spectral feature fitting algorithm

HyMap and SEBASS data were processed using the same methodology after the data were converted to apparent reflectance or apparent emissivity, respectively. The HyMap data were subset from 2.0-2.45  $\mu$ m and the SEBASS data were subset from 8.0-12.0  $\mu$ m prior to spectral feature analysis using Spectral Feature Fitting<sup>TM</sup> algorithm implemented in ENVI. This algorithm produces "scale" and "RMS" images using a least-squares fit and a gray-scale "fit" image that is a ratio of "Scale" to "RMS" images. False-color-composite images were created for interpretation by placing a mineral fit image in the R, G, and B color space. These same fit images can be classified using a statistical threshold of at least  $2\sigma$  as accurate mapping of the selected signature using the "fit" image (Riley and others, 2007).

# Library signatures for mineral mapping

There are numerous mineral libraries available for interpretations, including the Johns Hopkins University Spectral Library (Salisbury and others, 1991), Arizona State University Thermal Emission Spectral Library (Christensen and others, 2000), NASA Jet Propulsion Laboratory ASTER Spectral Library (NASA, 2000), and the USGS spectral library (Clark and others, 2007). Signatures with no absorption features such as quartz in the VIS–SWIR were not processed using the spectral feature fitting algorithm. The USGS mineral libraries were selected for mapping.

# DISCUSSION

# **ASTER data**

The ASTER band 4,5,6 false-color-composite image shows some areas of potential alteration (Figs. 4 and 5) associated with the porphyry copper deposits. Most of this alteration is in the Buckskin Range except for the alteration near the Blue Hill and the MacArthur pit in the Yerington district. Distribution of argillic, phyllic, and silicic alteration using ASTER is shown in Figure 6. There is some phyllic alteration in the vicinity of the Ann Mason porphyry deposit. Argillic alteration as mapped with the logical operators is primarily located in the Buckskin Range. These coherent patterns of alteration, especially phyllic alteration, provide areas of interest for future spectral analysis with hyperspectral imagery. Many of the areas mapped as containing potassic alteration were missed using the argillic, phyllic, and silicic ratios algorithms.

#### HyMap data

Propylitic alteration was estimated by using a falsecolor-composite, spectral-feature-fit image that estimated the presence of epidote, chlorite, and calcite. The spectral anomalies of that image set indicate a wide area of alteration (Fig. 7). This alteration anomaly is a white area that has been geochemically mapped by Dilles and others (2000) as actinolite alteration with moderate abundances of chlorite and epidote. The southwestern part of the white area is dominated by calcite and altered limestones. Rocks in the dark area south of the propylitic alteration are rocks that have not been extensively altered by hydrothermal fluids.

Argillic alteration was estimated by means of a falsecolor-composite image using chlorite and alunite spectral signatures; the image does not have any areas of white that would indicate the comparative abundance of kaolinite, chlorite, and alunite, the presence of which are interpreted as indicating argillic alteration (Fig. 8). The magenta area is a combination of kaolinite and alunite, and the green area is chlorite dominated. Several blue-toned areas indicate that alunite is the only significant alteration mineral present there. This image shows that there is no extensive argillic alteration in the vicinity of the area known porphyry copper deposits.

The mineral assemblage of kaolinite, muscovite, and illite is represented as a few white areas in a false-color-composite image that displays probable areas of phyllic alteration (Fig. 9). These minerals could be the result of weathering processes of these volcanic and sedimentary rocks. The rocks in the big, coherent pattern in the southern portion of the image are comparatively unaltered.

Figure 10 shows a false-color-composite image representing biotite, muscovite, and illite. The coherent, white pattern in the southern part of the figure indicates the assemblage of those three minerals, and the white area is nearly identical



Figure 4. Overview ASTER false-color composite image (4,5,6) of the Yerington District, Nevada and the surrounding region.

to the area seen in Figure 9. The volcanic and sedimentary rocks in that area contain some biotite. Both Figures 9 and 10, conversely, contain muscovite and illite; most of the minerals that are part of potassic alteration do not contain absorption features in the VNIR-SWIR.

# **SEBASS** data

SEBASS data were converted to apparent emissivity and used to produce coherent patterns for each mineral spectrum (Figs. 11-14) derived from the library spectra (Fig. 3) and a spectral feature fitting algorithm. Propylitic, argillic, and phyllic classes are the combined spectral responses of minerals that were mapped separately. These results show a general distribution of these minerals throughout the scene.

The false-color-composite image showing propylitic alteration minerals (Fig. 11) has a few white areas that represent the mineral assemblage of albite, epidote, and chlorite. Moreover, these white areas are near the Ann Mason porphyry copper deposit. There are several light-cyan areas that indicate the relative abundance of chlorite and albite, and those areas have a spatial coherence similar to the units in the underlying geology map of Proffett and Dilles (1984). The red areas especially in the southern part are epidote rich and associated with the skarn-rich area.

The false-color-composite image showing argillic alteration minerals (Fig. 12) has fewer white areas (showing the abundance of the mineral suite chlorite, kaolinite, and mont-



Figure 5. ASTER false-color-composite image (bands 4,5,6) of the Yerington district, Nevada.

morillonite) than those seen in the propylitic alteration image. Most of the areas are light pink and suggest a dominance of chlorite with lesser amounts of kaolinite and montmorillonite. This shows that chlorite is still present in areas that may be associated with argillic alteration. These images also show a spatial coherence with the underlying geologic map. The dark area in the southern part of the image has been mapped as andradite and diopside skarn alteration (Einaudi, 2000).

The phyllic alteration image (Fig. 13) showing the mineral suite quartz, muscovite, and chlorite does not have many white areas; white would indicate relatively large concentrations of muscovite, chlorite, and quartz. However, there is an extensive area of yellow suggesting that muscovite and chlorite are present. There are also several areas that are light magenta, indicating relatively higher abundance of muscovite and quartz, near the potassic alteration area mapped by Dilles and others (2000). Potassic alteration is represented in a false-color-composite image that represents orthoclase, biotite, and quartz (Fig. 14). Several magenta and light red areas are present in the area of potassic alteration by Dilles and others (2000). Magenta, here, indicates the relative presence of orthoclase with quartz, and red indicates the relative abundance of orthoclase. At the time of of this image analysis the adularia (low temperature) potassium feldspar spectrum was not available. The yellow areas (Fig. 14) are relatively orthoclase and biotite rich and correlate with the granitic plutonic rocks.

#### CONCLUSION

Mineral mapping with the logical operator algorithms mapped the alteration in the Buckskin Range. These logical operators and silica band ratio did not delineate potassic alteration or the actinolite rich alteration that is common in the



Figure 6. Argillic-phyllic-silica alteration image using logical operators for argillic (green) and phyllic (red) alteration and a band ratio for silica alteration (yellow) in the Yerington district, Nevada.

Yerington district. This mineral mapping with the multispectral satellite data shows the limits of these data in being able to map mineral alteration associated with potassic and silica alteration.

HyMap data false color composites show that these data can map minerals like kaolinite and alunite but are problematic for separating chlorite, epidote, calcite, and actinolite. The false-color-composite images of mineral-classification layers allow differentiation of multiple minerals for the same pixel. Determining hydrothermal mineral exploration vectors and accurate quantification using chlorite, epidote, calcite, and actinolite signatures is difficult because their absorption features overlap in the SWIR.

SEBASS data allow the discrimination of minerals associated with propylitic, argillic, phyllic, and potassic hydrothermal alteration. These results show that hyperspectral airborne emissivity data collected in the 7.5-13.5 µm wavelength region can delineate minerals that are associated with porphyry copper deposits. This analysis of minerals associated with propylitic, argillic, phyllic, or potassic alteration provides information about the distribution of these minerals which characterizes the porphyry copper hydrothermal alteration.

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Figure 7. Propylitic mineral alteration false-color-composite image using the "Fit" images processed with the Spectral Feature Fitting algorithm for the minerals epidote (R), chlorite (G), and calcite (B).



Figure 8. Argillic mineral alteration false-color-composite image using the "Fit" images processed with the Spectral Feature Fitting algorithm for the minerals kaolinite (R), chlorite (G), and alunite (B).



Figure 9. Phyllic mineral alteration false-color-composite image using the "Fit" images processed with the Spectral Feature Fitting algorithm for the minerals kaolinite (R), muscovite (G), and illite (B).



Figure 10. Potassic mineral alteration false-color-composite image using the "Fit" images processed with the Spectral Feature Fitting algorithm for the minerals biotite (R), muscovite (G), and illite (B).



Figure 11. False-color-composite image using epidote (R), chlorite (G), and albite (B) "Fit" images processed with the Spectral Feature Fitting algorithm using SEBASS data. Areas in white have high concentrations of epidote, chlorite, and albite.



Figure 12. False-color-composite image using chlorite (R), kaolinite (G), and montmorillonite (B) "Fit" images processed with the Spectral Feature Fitting algorithm using SEBASS data. Areas in white have high concentrations of chlorite, kaolinite, and montmorillonite.



Figure 13. False-color-composite image using muscovite (R), chlorite (G), and quartz (B) "Fit" images processed with the Spectral Feature Fitting algorithm using SEBASS data. Areas in white have high concentrations of muscovite, chlorite, and quartz.



Figure 14. False-color-composite image using orthoclase (R), biotite (G), and quartz (B) "Fit" images processed with the Spectral Feature Fitting algorithm using SEBASS data. Areas in white have high concentrations of orthoclase, biotite, and quartz.